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RE-INVENTION OR AGGORNIAMENTO? TIDAL POWER AT 30 YEARS

ROGER H. CHARLIER
Free University of Brussels, Belgium; HAECON NV, Ghent, Belgium

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Abstract—Electricity generation from the tides has been suggested for more than a century. No sizeable plant was ever built until France got the Rance River station off the drawing boards. The concept differs little from that of tide mills, providing mechanical power, that dotted coasts on both sides of the Atlantic. A companion paper retraces the history of the mills, to their decline and relatively recent resurgence. The paper assessed the performance and future of the utilization of tidal energy.

INTRODUCTION

The use of ocean energies to produce electricity was suggested by V. Romanoski in 1950 [1]. Even though he covers thermal, wave and tidal energy, it is the latter that is emphasized. Before him an exceptionally rich literature covered the topic [2, 3].

The subject comes up time and again, generating enthusiasm, controversy and opposition, but technology and economics have changed in favour of tidal power implementation. Ten years ago the Severn Tidal Power Group released an interim three volume report, funded in part by the British Ministry of Energy [4].

Two schemes had been examined, one a barrage alignment between Lavernock Point on the Welsh shore and Brean Down on the English shore—the so-called Cardiff–Weston line—and one far smaller with a barrage near English Stones, 8 km downstream from the Severn Bridge—known as the English Stones scheme.

Considering the similarities between tide mills, which at one time provided mechanical power on the coasts of the Atlantic ocean, and even on some rivers, it seems appropriate to ask: Is this an updating or rebirth of an ancient technology? Apart from the sophisticated electricity generating stations (France, Russia, China, Canada), the old tide mills appear to get a new lease on life, either as living museums or as local small energy providers.

WORKING PLANTS

A reputedly true anecdote holds that Charles de Gaulle, growing impatient of repeated references to the extraordinary power potential that the huge tides on the Armorican coasts held for France, quipped: "Let the thing be built". Thus the Electricité de France started

Table 1. Tidal-energy resources in Europe[a]

Country	Technically available tidal energy resource GW	TWh/year	European tidal resource (%)
United Kingdom	25.2	50.2	47.7
	(26.8)[b]	(49.5)[b]	—
France	22.8	44.4	42.1
Ireland	4.3	8.0	7.6
The Netherlands	1.0	1.8	1.8
Germany	0.4	0.8	0.7
Spain	0.07	0.13	0.1
Other European[c]	0	0	
Total Europe[c]	53.8	105.4	100.00

[a]Estimates based on parametric modeling.
[b]U.K. estimate based on more detailed barrage studies.
[c]Excluding former U.S.S.R.

construction of the tidal power station which celebrated its 30th anniversary in 1996. Lebarbier described candidly the performance of the first 15 years of operation [5], Gibrat described its construction in detail [6, 7], and Charlier reviewed and placed it in perspective [2]. Notwithstanding the celebration near the Rance River plant, it remains a fact that obviously France has shelved *sine die* the gigantic Chausey Scheme. There continues, nevertheless, to be rumblings about tidal power station construction. China and Korea seem to have taken the lead since the 1980s. Energy generation from the tides has gone a long way from the short-lived attempt at the end of the last century in Boston and the aborted works at the Aber Wrac'h (Brittany) or Passamaquoddy (Maine, U.S.A.).

Plans to transform this ocean energy into electrical energy were formulated since the 1920s; abortive attempts were made in Brittany in 1925 (Aber Wrac'h) and in the U.S.A. in 1933 (Fig. 1). Actually only two sizeable plants have been completed and are in current operation: one is located near St Malo on the Rance River (France), the other on Kislaya Bay (Russia) (Figs 3 and 4).

Sites

There are numerous suitable sites for tidal power electrical plants. Among these the Severn River (U.K.), the Kimberleys (Australia), Cabo Tres Puntas (Argentina), Passamaquoddy (U.S.A.) and the Bay of Fundy (Canada) were the subject of in-depth studies (Figs 5 and 6). The rating of a site is based upon tidal range, basin size, dam length and proximity to consumer market. Additional factors include characteristics of basin and foundation soils, and several other geological considerations. The "site value" is a coefficient introduced by Robert Gibrat, who built the Rance plant, and is the ratio of dam length to natural energy; the smaller the coefficient's value, the more desirable the site (Fig. 2).

The U.K. had, in 1930, a tidal power plant with pumped storage that provided 16 kw in the Avonmouth Docks. In the U.S.A. a tidal power plant with double basin arrangement functioned in the late 1880s. In Argentina sites include the Gulf of San Matias, the Straits

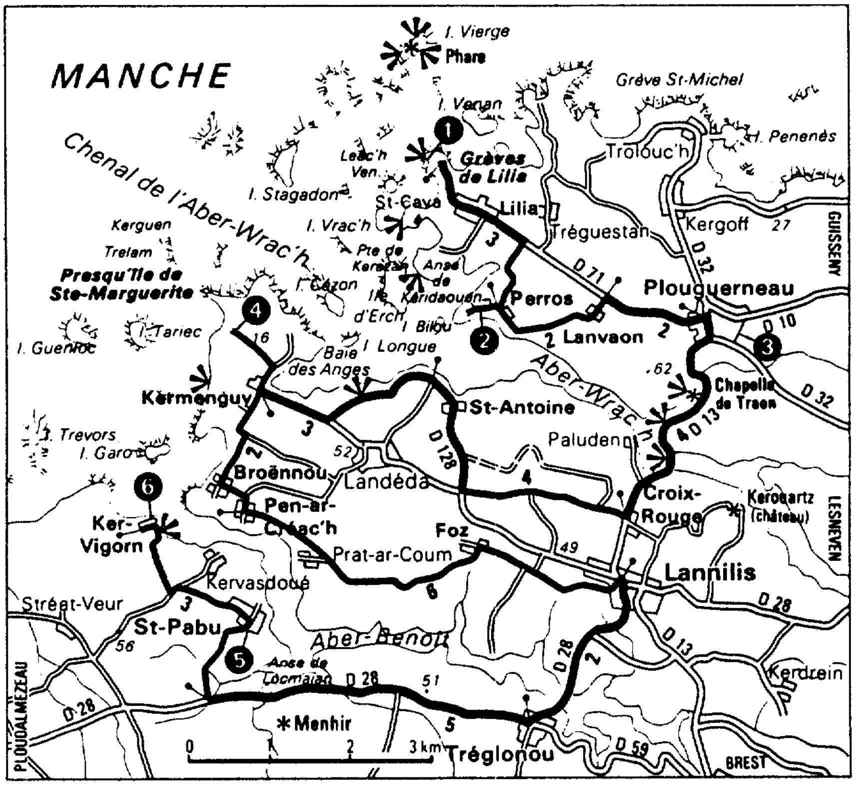

Fig. 1. Map. Aber Wrac'h.

of Magellan and the Bahia San Sebastian, and in Australia they include Shale Island, St George Basin and Rothsay Water. In Brazil possibilities exist in the territory of Amapa, Para and Maranhao (exploited by Sandotecnica). Here the Rio Bacanga has tidal barriers and only turbines would have to be installed to have a plant. Plans announced in 1988, but never implemented, would make the second largest plant in the world south of São Luis on the Bahia de São Marcos. In Ireland, with tides just below 5 m, power could be extracted on the Shannon River.

In the People's Republic of China, a power station was built in 1981 on Jianxia Creek in the Zhejiang estuary; a two-way generator thus provided 500 kW in 1981, but could be developed six-fold to perhaps produce 3 MW. China claims also to have built two ebb generation plants, one producing 40 kW since 1959 and upgraded in 1992 to 200 kW, the other producing 165 kW (Figs 10 and 11).

The French Rance River plant, now celebrating its 30th anniversary, provides about 500,000 kW. It has had, according to the builders—Electricité de France—negligible unfavourable environmental impact, but has strongly influenced the coastal region. It has created some new communities in the station's vicinity, shortened by about 30 km distances between St Malo and Dinard (a road passes across the dam), provided industrial potential for Brittany, and became a major tourist attraction. The plant is a symbol of innovation and has the advantage of functioning with perfect regularity and never running out of "fuel" (Fig. 7).

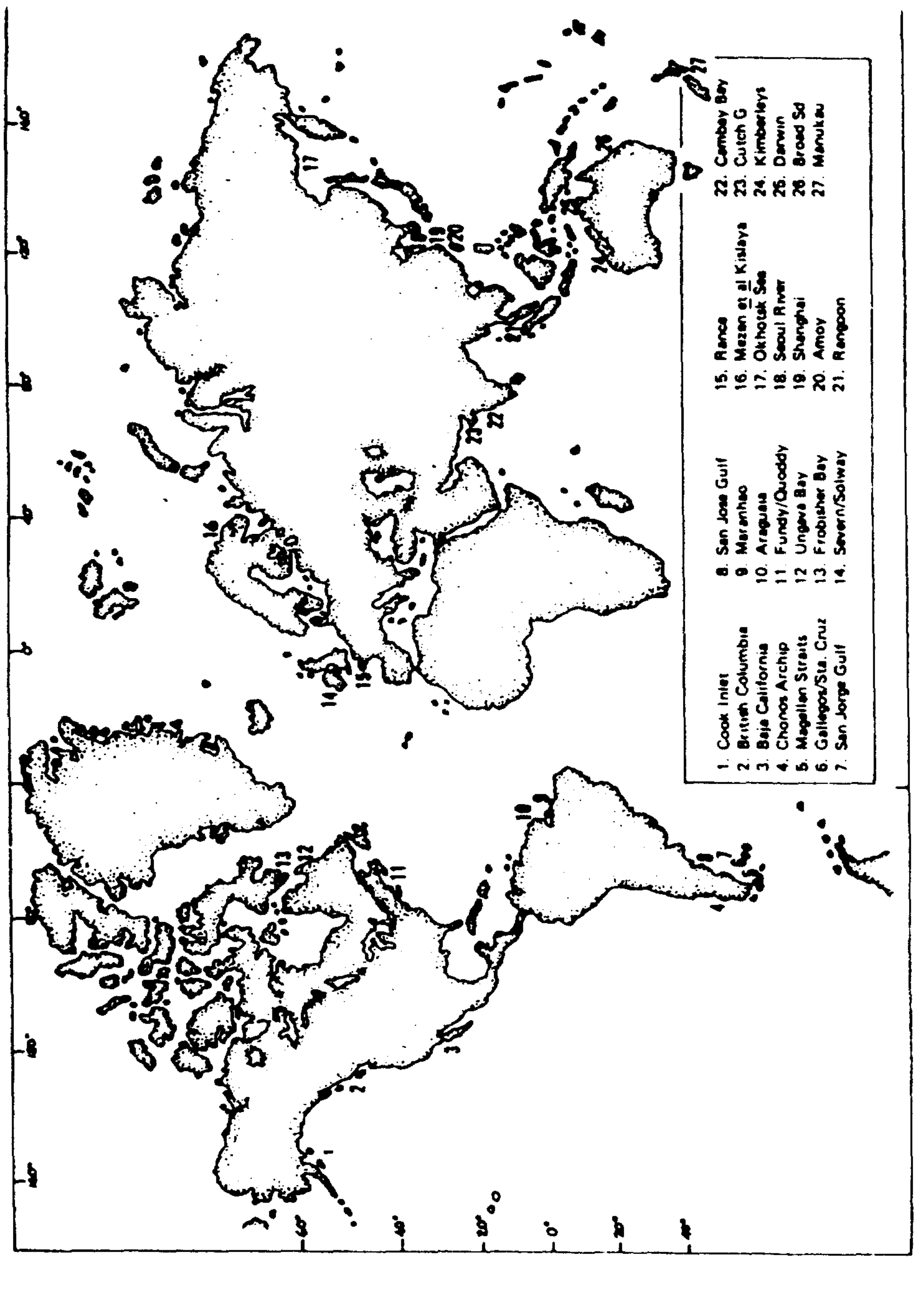

Fig. 2. Map. Major tidal power sites.

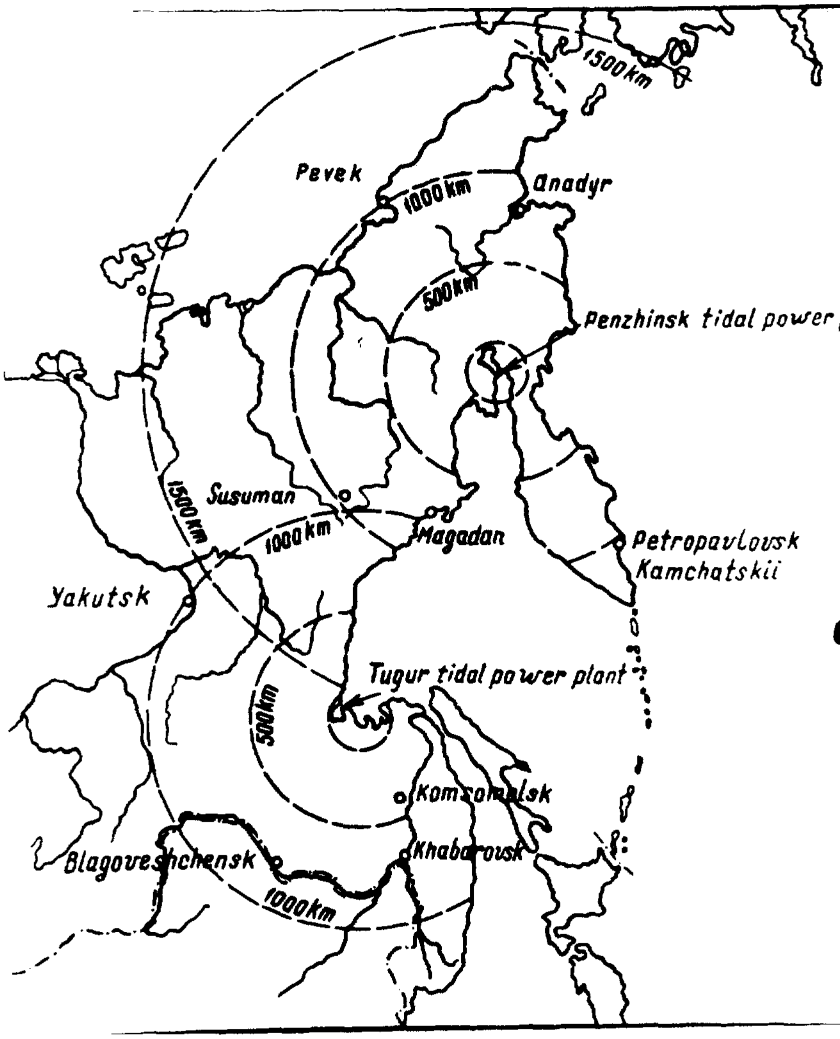

Fig. 3. Sketch map showing possible sites of large tidal power sites on the Sea of Okhotsk and zones of electrical power consumption (Russian Federation).

The greatest tidal amplitudes are found in the Bay of Fundy (16 m) and in the Passamaquoddy region (15 m). Some interest, in North America, has also been expressed in the Minas Basin (Nova Scotia) and Cook Inlet (Alaska). A Canadian scheme predicted production of 1300 kWh and an American plant proposed by General Electric foresaw 1594 million kWh for a plant which would have cost, in 1927, less than one-tenth of the current price to build. Both F. D. Roosevelt and J. F. Kennedy were interested in such undertaking.

Franklin Roosevelt allocated $7 million in 1935 to construct a tidal power plant in Passamaquoddy Bay where once tide mills had operated. Entirely on U.S.A. territory, work started the same year on Cobscook Bay (Maine). The final scheme viewed a two-nation,

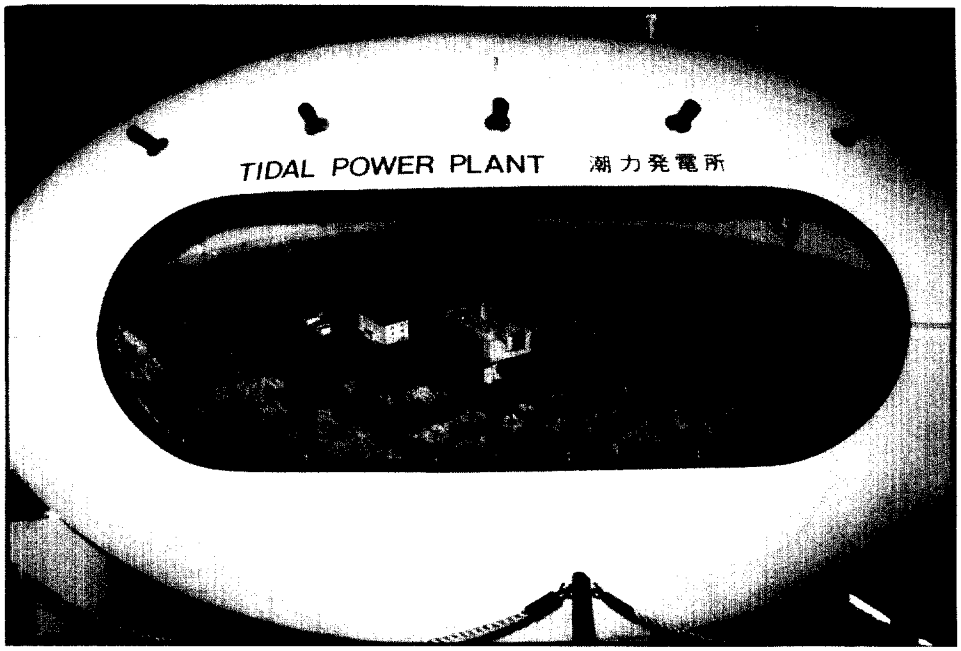

Fig. 4. Mock-up of Kislaya Bay tidal power station (Russ. Fed.).

Fig. 5. President F. D. Roosevelt examining Passamaquoddy tidal power site and plant model.

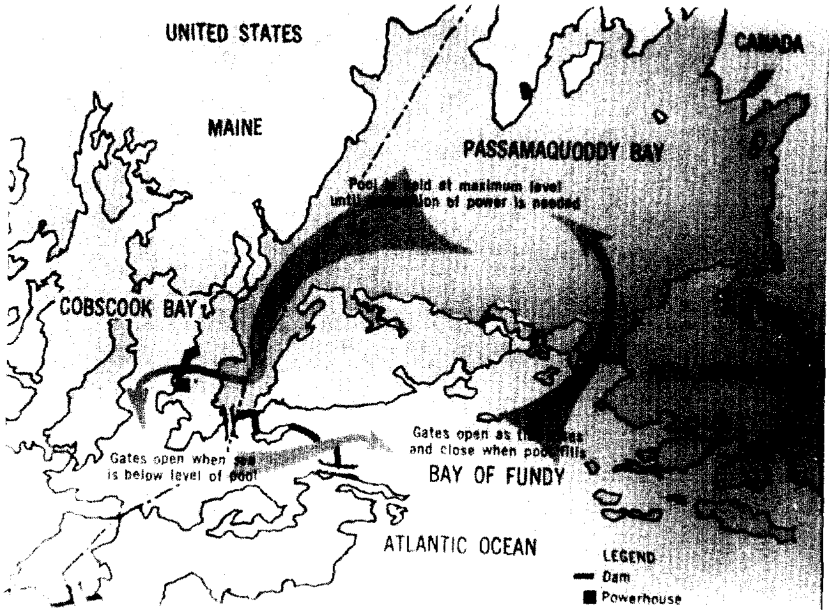

Fig. 6. Map. Passamaquoddy Bay area.

Fig. 7. La Rance River power plant (Brittany, France). (Photographed by M. Brigaud, Electricité de France.)

Fig. 8. Annapolis-Royal tidal power station under construction (Nova Scotia, Canada). (Nova Scotia Department of Tourism & Information.)

Fig. 9. Aerial view of Annapolis-Royal tidal power station. (Photograph courtesy of Nova Scotia Department of Tourism & Information.)

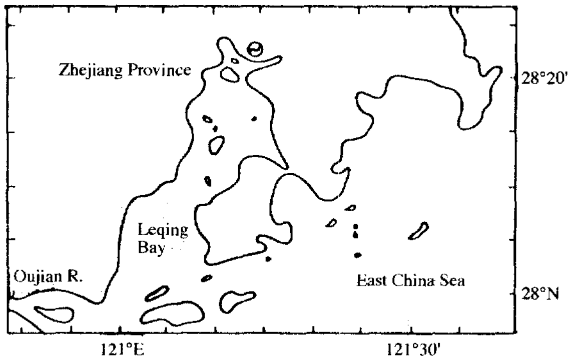

Fig. 10. Map. Jiangxia tidal power station (P. R. China). *Source*: Ref. [31].

two-pool station. With two dams completed in 1936, the 5000 workers were laid off when the U.S. Congress cut appropriations. Total mothballing ensued when, in protest against an exclusively American scheme, the U.S. Federal Power Commission issued a negative report.

Found economically viable for the U.S.A., a 1959 report recommended Shepody Bay–Cumberland Basin as the best site and the one with the most favourable economic conditions. The Minas Basin, rated uneconomical in 1956, came under study again in 1965, but Passamaquoddy periodically rises from its ashes. J. F. Kennedy tried, with full support from the Secretary of the Interior, to revive the project, but again Congress failed to fund the project.

Cook Inlet (Alaska) has mean tidal ranges of 7.65 m (25 ft) near Anchorage. Several sites are favourable for a plant and an energy potential of 18,600 GWh/year has been calculated for Turnagain and Knik Arm reservoirs (Wilson & Swales) [8a]. In 1977 a U.S. Department of Energy study covering sites in Passamoquoddy Bay and Cook Inlet found the conventional cost/benefit ratio unfavourable [8b], but a 50-year span life-cycle cost analysis turned Passamaquoddy into an "extremely attractive project", and recommended implementation (Fig. 6).

The Argentinian potential involves many sites, predominantly the San José and San Jorge gulfs. The latter one alone could provide 10,000 million kWh (7457 million hph). The proponents of a Severn River plant near the Bristol Channel estimated on 800 MW. If the implementation does not occur of what could be the largest single hydro-electric system in Southeast Asia, due to the region's remoteness and lack of a current market, some 50 sites have been examined along 1700 km (932 miles) of coastline in Northwestern Australia as possible alternatives—resources from Broome to Darwin Harbour amount to 300 million kW (224 million hp).

Canada completed a pilot tidal power plant, with a new type of hydro-turbine in Nova Scotia. The final choice, for an experimental station, was the Cumberland Basin; a pilot plant was completed, in 1982, at Annapolis-Royal (Figs 8 and 9).

THE TIDAL POWER PLANT

Basically there has not been a great departure, in design or system, from the centuries-old tide mill: both the mill and the tidal power plant involve a "powerhouse", a barrage,

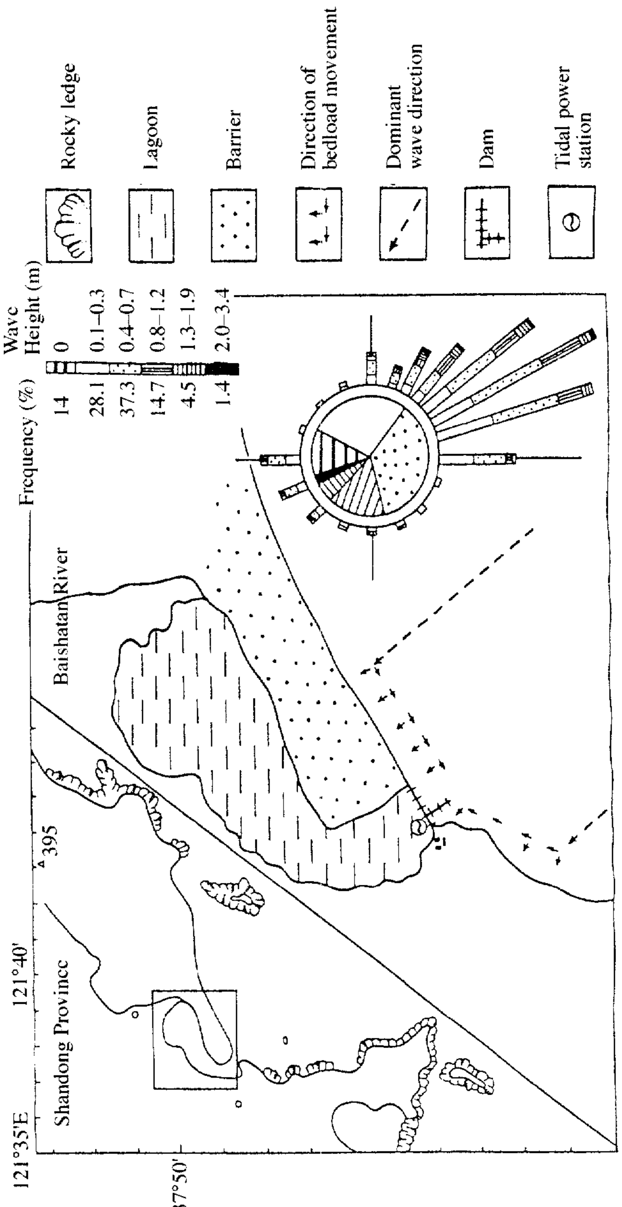

Fig. 11. The Raishakou tidal power station (P. R. China). *Source*: Ref. [31].

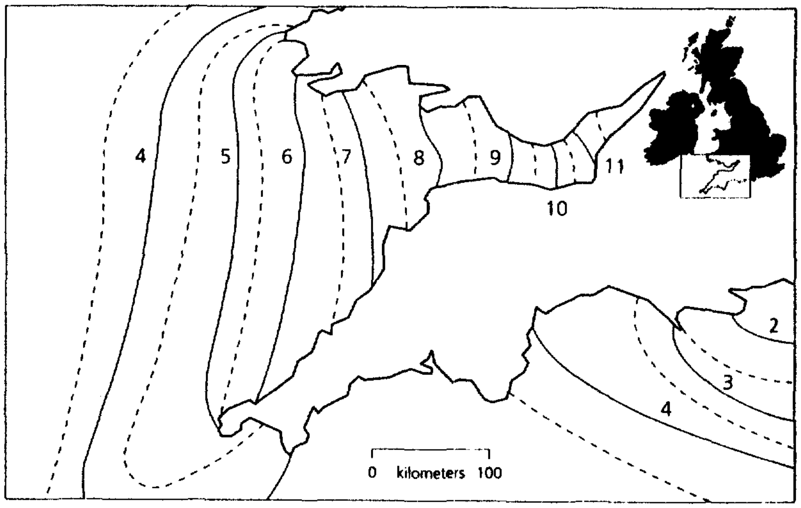

Fig. 12. Canada. Combination of local effects create mean tidal range exceeding 11 m (+/− 33 ft). Iso-lines interval: 0.5 m (1.5 ft). *Source*: Ref. [32].

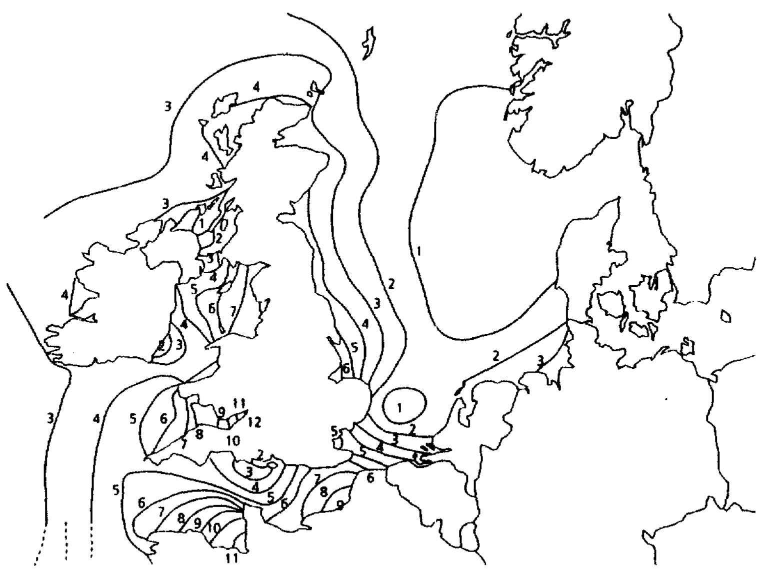

Fig. 13. NW Europe. Mean spring tidal range in metres. *Source*: Ref. [33].

and an impounding (or retaining) basin. Where the mill extracted energy and transformed it into mechanical power, the modern plant transforms tidal energy into electricity. The technical feasibility was proven by the construction of the Rance River Plant [6] and its successful operation for over 15 years [9] (now already 30 years). Economic considerations,

particularly capital investments, have been the deterrent against construction of new plants. There is no unanimity, however, whether currently tidal power is or is not competitive with other sources of electricity. One thing is certain: it is safe and the environmental impact is apparently benign [2, 7].

The lessons from the Rance plant

The Rance River plant was constructed "in the dry", requiring expensive civil engineering work: the building—and subsequent removal—of cofferdams (Fig. 3). The Soviet engineers dispensed with these and instead constructed powerhouse and sluices by modules on land: the caissons were then towed to the site and sunk in place on pre-arranged foundations [10]. The method has been further honed and it is a foregone conclusion that future plants will mostly, possibly all, follow the caisson construction approach [11].

With the lone exception of the turn of the century ill-fated double-basin Boston Bay scheme, all plants built so far, and currently contemplated, are single basin tidal power facilities; both the Rance and the Kislaya plants are double-effect electricity generating stations using bulb turbines (Fig. 4). In this regard, major changes may affect future plants. Wilson [12, 13] and Wilson and Gibson [14] have expressed strong reserves concerning the need to install bulb turbines that provide double-effect (ebb and flood) generation. Doubts have been expressed as to the economic return of pumping and ebb tide generation, all possible with the bulb turbine. Instead, the straight-flow turbine with rim-type generator (Straflo unit) is being suggested as a more economic, perhaps more efficient system; the Straflo turbine has been installed, and tested, in the Annapolis-Royal (Nova Scotia) pilot tidal power plant completed in 1982. This turbine is a modern version of the axial-flow turbine patented in 1919 by Leroy Harz [15–17]; the low head propeller turbine is placed in a horizontal water passage and its field poles are attached to a rotor rim mounted on the periphery of the propeller. By being attached to the rim, a larger rotor diameter is attained thereby providing larger inertia and better stability; the electrical performance is improved and higher generator ratings can be attained. The Annapolis-Royal plant turbine has a 7.6 m (24.9 ft) diameter runner, four-blade propeller and it is foreseen that 50 GWh/year will be generated.

A lesson to be drawn from the Kislaya plant is that not only can schemes be built and successfully operated under extremely harsh climatic conditions (Soviet Arctic), but that small plants may have considerable local or regional value. Small facilities require a far more modest capital investment and may provide the limited amount of power needed to lift isolated regions out of economic stagnation. A major expense is naturally the construction of a dam: the Chinese plant and the Annapolis-Royal station made use of existing dams; Gorlov proposed using, instead of a rigid dam, a thin plastic barrier hermetically anchored to the bottom and bay sides, and supported by a bay-spanning cable attached to several floats [18, 19]. Furthermore, the tidal energy would be converted into power through use of compressed air. The flow of water drives a large piston of an air motor; electricity can be generated directly or the compressed air can be stored for later release and power generation. Gorlov showed that a high-velocity air-jet can be provided for even very small water heads and is sufficient for industrial-size air turbines. Water passing through a specialized air chamber placed on the ocean floor across a flowing watercourse acts as a natural piston compressing air in the upper portion of the closure; the compressed air drives an air turbine. Decreased water pressure makes it possible to use light plastic barriers instead of conventional rigid dams.

Suitable for plants of almost every power, even for individual consumption, the system makes a great number of ultra-low-head water flows (small rivers, brooks and canals) and increases the number of potential tidal power plant sites.

The system includes an air changer of waterproof—reinforced concrete or steel—installed on the ocean floor that converts the energy from water into compressed air. Several chambers can be assembled in a single system; a barrier that creates a water head and directs the water stream from the upper to lower basin; and the powerhouse, containing a number of air turbine-generator units.

In one mode of chamber operation, air expands through the turbine to the atmosphere (compressed cycle), followed by suction of the air from the atmosphere, through the turbine into the chamber (vacuum cycle). Another mode of operation, chamber to chamber, involves at least two adjacent air chambers; it doubles the working air jet pressure compared to the preceding mode.

An important aspect of both Gorlov's proposal and the Straflo turbine is that because such turbines require only very low operational heads, the number of sites suitable for tidal energy extraction has been spectacularly increased; additionally, development of a low-pressure air-turbine on an industrial scale would strengthen the competitive position of total hydropneumatic power plants.

Usable in both river and tidal current, the open and ducted vertical axis turbine, or Turbodyne Generator, is an ultra-low head turbine which has the ability to operate on only the kinetic head of the water current. The operational principle is the same as that of the Darrieus vertical axis wind turbine, but the Turbodyne Generator has straight working blades rather than curved ones; this is possible because of the relatively lower rotational speeds and a smaller possible range of operating conditions. Among the many advantages of the Turbodyne Generator is the lesser amount of turbine material required as its cross-sectional area is small: capital costs are thus reduced; the turbine has high performance characteristics at low overheads as shown theoretically and in field tests.

Multiple or single basin schemes?

Although virtually all tidal power projects now under consideration discard the idea of a second basin—which would, however, permit retiming of power—Bickley and Ryrie favour the system for the Severn River estuary [20]. This estuary possesses the second highest tidal range in the world.

Because the level of power demand depends on season, time of day, and other factors, and assuming a scheme has been implemented, a second tidal power scheme operating in a flood generating model alongside the first would generate the power while the first is refilling its basin; added flexibility could be achieved if some turbines were sited between the two basins.

The purpose of the additional scheme is to generate energy during the day and in doing so, reduce the variation in demand on the rest of the U.K. General Electricity Generating Board (G.E.G.B.). Operating this scheme can be done in a constrained, or even unconstrained, way which means that the output of the main basin is not restricted to the specific power demand. This scheme could operate on either model, though the alternating mode has been suggested and might achieve best annual aggregate performance [21].

The problem of large discontinuities in power at the beginning and end of each period would be solved by the second basin which would regulate the time of generation to the pattern of power demand.

A double-effect generator has been ruled out for this estuary because of reduction in power output and less efficient and more expensive turbines which would have to be capable of generating in both directions. The Bickley and Ryrie study admits, however, that at present the benefit/cost ratio is not attractive. For it to be attractive, income would have to be increased without higher operating costs.

ENVIRONMENTAL IMPACT

No major environmental impact study was ever carried out for the Rance River plant. No information has been made available regarding the Soviet and Chinese schemes. Basically the impact of the Rance plant has been benign ; tidal characteristics have been affected, navigation patterns have been modified, and changes have occurred in the level of the pool. Only *lanzons* (a local fish) have disappeared, but oyster culture has been substantially improved. Gibrat made a short report based on six years of operation of the Rance [7]. A far more extensive study was conducted for the Severn River [22]; environmental effects were also discussed by Waller [23].

Tidal power affects the environment less than hydroelectric plants since no flooding of land areas is necessary to create a reservoir [2].

An assessment of impact upon tidal range, water boundaries and sediment movements was made by Greenberg using a numerical model [24]. He considered large tidal barriers. The spring tidal range in the Bay of Fundy and the Gulf of Maine is over 15 m (49.2 ft). Resonance effects have often been attributed to being the cause of these unusually high tides. Different mathematical models have been proposed to calculate the period of this tidal cycle. Many of the results did not agree but considerations of the coefficient of friction and use of newer observations seem to result in a fundamental period of 12.33 h. The effects of barriers was integrated into the mathematical models. The barrier caused an increase and decrease in the tidal amplitude and a small change in phase which depended on where the barriers were located.

As for the boundary between the stratified and well-mixed areas as calculated from the numerical model, it was found that the model agrees with observations taken in the tidal region: the model cited that the reservoirs contained by the barrages increased in stratification. Only the seaward side of the barrier showed little change in stratification.

The third study investigated suspended sediment movements. Large quantities of fine clays are suspended in the waters at the head of the Bay of Fundy. Though difficult to give quantitative results, there would be, outside the barrier, a slight increase in sedimentation and a significant increase in sedimentation occurring on the near shore of the reservoir. Near the barrier itself some sedimentation will occur in slack water but filling and generation cycles would produce currents strong enough to resuspend the material deposited.

An 8–9 km (5–5.6 miles) rock-filled barrage across the mouth of Cobequid Bay in the Bay of Fundy/Gulf of Maine area would have effects landward (300 km^2 (116 square miles) of Cobequid Bay) while significant effects seaward may extend up to 300 km (186 miles) out to sea from the barrage.

Current design concepts favour ebb flow power generation which involves holding the water filling the head pond at high tide, then returning it through turbines at low tide. As a consequence, the water level on the head pond will fill only to the mid-tide level, allowing much of the current intertidal area to become a permanently submerged subtidal zone.

These changes on water flow will also decrease turbidity leading to an increase in sedimentation in the head pond. Particle size distribution will change at any given location.

The cycle of deposition and erosion of intertidal sediments normally is influenced by tides, river output, ice rafting, and storms. The barrage will diminish the effects of storms and river flows from removing deposits, while increased ice formation will alter the distribution patterns.

Increased stratification of waters will result in an increase on peripheral ice in winter and its persistence in spring. This ice cover may affect mean air temperature and the length of the growing season in the area as occurred with the Annapolis causeway. Higher summer water temperatures will increase the fog occurrence. Control of the water level will provide increased flood controls, although local drainage may slow from higher water levels. Existing erosion in the area should decrease [25].

Seaward of the barrage and near the barrage a reduction in tidal amplitude is expected, although the magnitude is highly dependent on the number and location of the turbines. This change will reduce the intertidal zone and relocate areas of maximum erosion. Tidal amplitude reduction will be accompanied by some reduction on tidal currents and increase the siltation of existing harbours, further limiting their use.

Reflected waves from the barrage and new sluicing currents will change current distributions of tidal sand and mud flats, having significant biological consequences [25].

An increased tidal amplitude at the mouth of the Bay of Fundy may increase upwelling in the area, increasing biological production.

Biological implications of barrage construction are several. Approximately half of the existing intertidal zone, landward of the barrage, will become a subtidal region, resulting in the elimination of several fish species [26]. Saltwater marshes will expand inland while water exchanges will decrease. A reduction of the tidal range will in turn reduce the size of mudflats and marshes and this in turn will influence the reproduction of migratory seabirds and fishes inhabiting the bay's inner regions; where the range will increase (outer part) production of intertidal algae will be enhanced.

Daborn disputes, in fact, that the impact of a Bay of Fundy plant would be negligible, placing the strain on tidal regime modifications and current velocity changes.

Tidal power poses no engineering problems. If more plants have not been built reasons are to be found in construction costs, economic considerations and problems caused by phases of the moon. However, as predicted by Sir John Hacking: "... schemes ... uneconomic at present [are] expected to be economic in the near future". Since then transmission systems have been considerably improved, reversible blade turbines permit electricity production at ebb and flow, and the use of daily and intersyzygial control. In the 1960s construction costs of a tidal power station was $2\frac{1}{2}$ times as high as an equivalent conventional hydroelectric station, with cofferdams accounting for 30% of total costs. The Soviets cut down on investment by assembling on the site a plant built in "modules" on land.

Nuclear power seemed less expensive but economics have changed and tidal power may well become competitive cost-wise according to a Canadian study. French findings claim that it is now cheaper than conventional hydropower and nuclear power [27]. It cannot be a replacement for other energy sources; however, what it can become is an important additional suppletive source, particularly in areas otherwise deprived of energy resources. While tidal ranges of at least 9 or 10 m (28.5–32.8 ft) were considered necessary for an economically viable plant, smaller amplitudes do not automatically disqualify a site. Most thought has been along the lines of major plants. However, small schemes could be very

valuable along coasts, particularly in developing nations, to spur on regional as opposed to national and international growth.

In 1996 sites "under consideration" and "suitable" had changed little from the survey made in 1982 or 1993 [2, 3]. They included: Gulf of San José (Argentina), Secure Bay (Australia), Canada (cf. *supra*), India (Kutch and Cambay Gulfs), Korea (Garolim and Cheonsu), Mexico (Rio Colorado and Tiburon Island), U.K. (Severn, Mersey, Wyre and Conwy), U.S.A. (cf. *supra*), and Russia (cf. *supra*). Of the existing plants installed capacity and output are:

La Rance (1966)	240 MW	540 GW/year
Annapolis-Royal (1984)	17.8	30
Jhianxhia, China (1980)	3.2	11
China, other sites (1984–)	1.8	Unknown
Kislaya (1968)	0.4	Unknown

The future of tidal power remains a matter of economics, and perhaps of politics as well [28].

The 1977 Shaw study of the Severn River was followed by a pre-feasibility study that spanned the years 1978–1981 [22]. Four concerns were identified at the onset:

(1) *Water quality in the estuary*: the strong flushing action of the high tide has led many industries with problem effluents to locate on the banks of the estuary and several urban areas discharge untreated wastes into the estuary. Though mixing would be reduced, the aquatic ecosystems would benefit.

(2) *Wading birds*: the estuary is a feeding area of international importance for six species of wading birds. The area would be reduced.

(3) *Passage of migratory fish*: The Severn and its tributaries are important salmon rivers. Fishways may provide an acceptable solution.

(4) *Effects on navigation to the major ports of the estuary*: changes in tides and the need to navigate extra locks could drive some shipping trade away [29]. Approximately 18 months into the study three barrage schemes were selected for more detailed evaluation. The scheme with the farthest in barrage received the most attention since it was also the first phase in a staged scheme.

The study identified no insurmountable environmental impacts while admitting that additional studies needed to be done at further stages [30].

CONCLUSION

The technological feasibility of both major and minor tidal power schemes has been proven. The environmental impact, notwithstanding some reservations, is limited; in many sites the economic and sociological consequences are very favourable. Further improvements in construction, civil works, turbine design and other facets will increase price competitiveness. Already the costs of building a nuclear plant are close to those of a tidal power plant whose lifespan is longer.

REFERENCES

1. Romanoski, V., *Les Energies de la Mer* (*Collection Que sais-je?*). University Press of France, Paris, 1950.

2. Charlier, R. H., *Tidal Energy*. Van Nostrand-Reinhold, New York, 1982.
3. Charlier, R. H. and Justus, J. R., *Ocean Energies. Environmental, economic and technological aspects of alternative power sources*. Elsevier, Amsterdam, London, New York, Tokyo. Oceanography Series, 1993, **56**, 1–3 & 273–346.
4. Severn, R. T., Dinsley, D. L. and Hawker, L. E., Tidal power and coastal management. *Proc. 13th Symp. Colston Res. Soc.*, Bristol, Scientechnica, 1979.
5. Lebarbier, C. H., Power from the tides. *Nav. Eng. J.*, 1975, **87**(3), 52–56.
6. Gibrat, R., L'énergie des marées: Paris, Presses Universitaires de France, 1966.
7. Gibrat, R., L'énergie marémotrice dans le monde: l'usine marémotrice de la Rance et l'environment. *La Houille Blanche*, 1973, **211**(2–3), 145–151.
8. (a) Wilson, E. M. and Swales, M. C., Tidal power from Cook Inlet, Alaska. In ed. T. J. Gray and O. K. Gashus, *Tidal Power*, Plenum Press, New York, 1972, pp. 239–256. (b) Wayne, W. W., *The current status of tidal power: Coursebook Key Biscayne National Symposium on Energy and the Oceans*. U.S. Department of Energy, 1977, pp. 7–58.
9. Banal, M. and Bichon, A., Tidal energy in France. The Rance tidal power station. Some results after 15 years of operation. *Int. Symp. Wave and Tidal Energy* [Cambridge], II, 1981.
10. Bernshtein, L. B., Russian tidal power station is precast offsite, floated into place. *Civil Eng.*, 1974, **44**(4), 46–49.
11. Clare, R. and Oakley, A. J., The towing and positioning of caissons in a tidal barrage. *Int. Symp. Wave and Tidal Energy* [Cambridge] II, 1981.
12. Wilson, E. M., Energy from the sea—tidal power. *Underwater J.*, 1973, **5**(4), 175–186.
13. Wilson, E. M., Tidal energy and system planning. *Consulting Engineer* [London], 1977, **41**(4) 25.
14. Wilson, E. M. and Gibson, R. A., Studies in retiming tidal energy. *Proc. Int. Symp. Wave and Tidal Energy* [Canterbury], 1978, pp. 1–10.
15. Douma, A., Stewart, G. D. and Meier, W., Straflo turbine at Annapolis Royal—First tidal power plant in the Bay of Fundy. *Escher Wyss News*, 1982, **62**, 957–966.
16. Miller, H., *Die Straflo Turbine; die technische Realisation von Harza's Idëen*. Zurich, Straflo-Group (Escher-Wyss), 1975.
17. Miller, H. and Wilson, E. M., Optimizing Straflo turbines for tidal applications. *Proc. Int. Symp. Wave and Tidal Energy* [Cambridge], II, 1981.
18. Gorlov, A. M., Some new conceptions in the approach to harnessing tidal energy. In *Proc. Miami Int. Conf. on Altern. Energy Sources*, 1979, II, 1171–1195.
19. Gorlov, A. M., Hydropneumatic approach to tidal power. *Int. Conf. on New Approaches to Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982, II-5. (See also: Charlier, R. H. and Justus, J., *Ocean Energies*. cf. [2] pp. 345–346.)
20. Bickley, D. T. and Ryrie, S. C., A two-basin tidal power scheme for the Severn Estuary. In *Int. Conf. New Approaches to Tidal Power*. N. S. Dartmouth, May 31–June 3, 1982, IV-1.
21. Binnie and Partners, *Severn tidal power—Alternative assessment of fuel savings*. London, U.K. Department of Energy, Report Nr. STP-85, Aug. 1981.
22. Shaw, T. L., ed., *An environmental appraisal of the Severn Barrage*, Bristol. The University—Dept. of Civ. Engng, 1977.
23. Waller, D. H., Environmental effects of tidal power development. In *Proc. Int. Conf. Utliz. of Tidal Power*; also in ed. T. J Gray, and O. K. Gashus, *Tidal Power*, Plenum Press, New York, 1970, pp. 611–625.
24. Greenberg, D., Bay of Fundy tidal power; mathematical studies. *Int. Conf. New Approaches on Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982, III-1.
25. Daborn, G. R., Biological consequences of the Minas Basin tidal power proposal. In

Int. Conf. New Approaches on Tidal Power, N. S. Dartmouth, May 31–June 3, 1982, III-2.

26. Risk, M. J. *et al.*, Aspects of the marine ecology of the Minas Basin relevant to tidal power development. In *Fundy tidal power and the environment*, ed. G. R. Daborn, N. S. Wolfville, Acadia University, 1977, pp. 164–179.
27. *Sea Technology*, November 1996.
28. Charlier, R. H., Whatever happened to tidal power? Waiting for the political pull. *Oceans*, 1981, **14**(6), 30–34.
29. Heaps, N., Prediction of tidal elevations. Model studies for the Severn barrage. In *Proc. Severn Barr. Symp.*, London, Oct. 1981, 35–42.
30. Ruxton, T. D., Overview of the environmental aspects of the Severn development. *Int. Conf. New Approaches on Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982, III-3.
31. Zhenzia, L., Donking, X. and Mingzuo, F., Evaluation on sites of two tidal power stations. *Coastal Zone '89*, 1989, 2203–2209.
32. Cavanagh, J. E., Clarke, J. H. and Price, R., Ocean energy systems. In ed. T. B. Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, *Renewable energy. Sources for fuels and electricity*. London, Earthscan & Washington, Island Press, 1993, pp. 513–548.
33. Ackers, P., Tidal power projects—Australia. In ed. R. T. Severn, D. L. Dineley, and L. E. Hawker. *Proc. 30th Symp. of the Colston Research Soc.*, The Society, Bristol, 1978.
34. André, H., Ten years of experience at the "La Rance" tidal power plant. *Ocean Manage.*, 1978, **4**,(2–4), 165–178.
35. Anonymous, Brazil plans tidal power plant. *Water Power & Dam Construction*, 1987.
36. Anonymous, China looks to tidal power. *Elec. Rev.*, 1981, **3**, 208.
37. Anonymous [Energy Technology Support Unit], *Mersey barrage feasibility study; stage* 2 (doc. ETSU TID 4071). Abingdon, UK, Department of Energy, 1991.
38. Anonymous, Ocean energy. In *World Energy Conference; World Energy Conference Committee on Renewable Energy Sources, Opportunities and Constraints* 1990–2000, 1992, Chapter 3.
39. Anonymous, *Papers of the symposium on the Rance Plant 30th anniversary*, St Malo, Electricité de France, 1996.
40. Baker, A. C., *Tidal power*. London, Peregrinns [IEE], 1991.
41. Baird, H., Upgrading of low head density hydraulic energy, making it more acceptable for putting through a conventional hydro turbine. In *Int. Conf. New Approaches to Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982.
42. Bernstein, L. B., Kislayaguba experimental tidal power plant and the problem of use of tidal energy. In *Tidal Power*, ed. T. J. Gray and O. K. Gashus, Plenum, New York, 1972, 215–238.
43. Cambel, A. B., *Tidal power—its promise and problems*. Durham, Univ. of New Hampshire, Centre for industrial and institutional development, 1980.
44. Daborn, G. R., *Fundy tidal power and the environment*. In *Proc. Workshop Env. Implic. Fundy Tidal Power*. Acadia University, N. S. Wolfsville [Publ. 28], 1977.
45. Davis, B. V. and Swan, D. H., Extracting energy from river and tidal currents using open and ducted vertical axis turbines. *Int. Conf. New Approaches to Tidal Power* [N. S. Dartmouth, May 31–June 3, 1982], II-1.
46. Debelius, C. A. and Whitewell, R. G., A preliminary assessment of Cook Inlet tidal power. In *Proc. 2nd Int. Symp. on wave and tidal energy* (BHRA), 1981.
47. Delory, R. P., Prototype of tidal power plant achieves 99% availability. *Sulzer Technical Rev.*, 1987.
48. Douma, A. and Stewart, G. D., Annapolis Straflo turbine will demonstrate Bay of Fundy tidal power concept. *Modern Power Systems*, 1981, **1**, 53–65.

49. Electrobras, *Maremotriz estuario do Bacanja Projecto conceitul.* Min. Min. & Energy of Brazil [energy model] May. ICE (GB), 1990, Severn and Mersey rivers. Developments in tidal energy. In *Proc. 3rd Int. Conf. on Tidal Power*, London, Telford, 1981.
50. Keefer, B. G., Optimization approach to tidal energy. *Int. Conf. New Approaches to Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982, I-3.
51. Lewis, J. G., The tidal power resources of the Kimberleys. *J. of the Inst. of Eng., Austral.* 1963, **35**(12), 333–345.
52. Meier, W. and Miller, H., Die Entwicklung zur Straflo-Turbine. *SEV/VSE Bull.*, 1978, **69**, 17.
53. Miller, H., Choice of hydro-electric equipment for tidal energy. *Proc. Korea Tidal Power Symp.* [Seoul] Nov. 14/15, Korean Ocean Research and Devel. Inst., Seoul, 1978.
54. Robinson, I. S., Enhancement of power availability by tuning the operation of the tidal barriers to match the tidal dynamics. *Int. Conf. New Approaches to Tidal Power*, N. S. Dartmouth, May 31–June 3, 1982, 1–2.
55. Robinson, I. S., Tidal power from the wedge-shaped estuaries. An analytical wedge model with friction, applied to the Bristol Channel. *Geophys. J. Roy. Astr. Soc.*, 1981, **62**, 77–95.
56. Robinson, I. S. and Perry, J. M., Tidal power from rectangular estuaries : tidal dynamics constraints. In *Proc. Am. Soc. Civ. Eng. J. Hydrol. Div.*, 1980, 106, HY 11, 1915–1934.
57. Sogreah, *Construccon del Canal San José.* Grenoble (France), Soc. d'Etudes et d'Applications Hydrauliques, 1959.
58. Wick, G. L. and Schmitt, W. R., *Harvesting ocean energy.* UNESCO Press, New York, 1981.
59. Wilson, E. M., The Solway Firth tidal power project, *Water power*, 1965, **17** (11), 431–440.
60. Zu-Tian, Ge, The development of tidal resources in China. The tidal experimental station of Jiangia and its number 1 and 2 bidirectional tidal water turbine. In *Ocean energy recovery, ICOER* 89, *Proc. Int. Conf. Ocean Energy Comm.*, ed. H. J. Krock. ASCE, Water, Ports & Coasts, Ocean Div. The Society, New York, 1989 pp., 157–166.